Experimental Status of the CKM angle β

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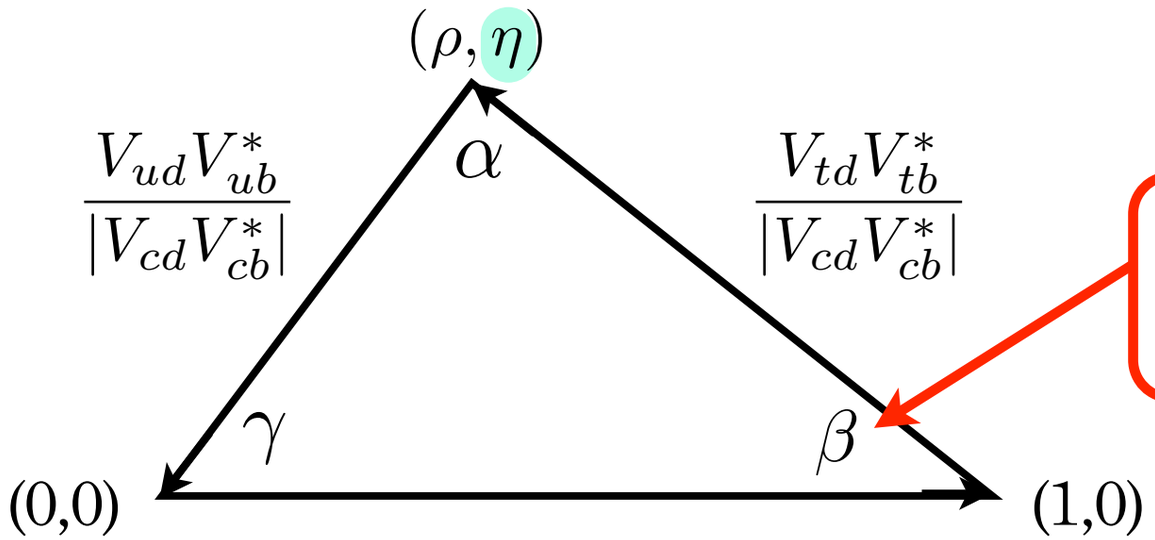
CP violation in Standard Model

- Arises from single phase in CKM matrix:

$\lambda \equiv \sin\theta_{\text{Cabibbo}}$

$$V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

- Unitarity of V_{CKM} can be represented as a triangle in the complex plane:

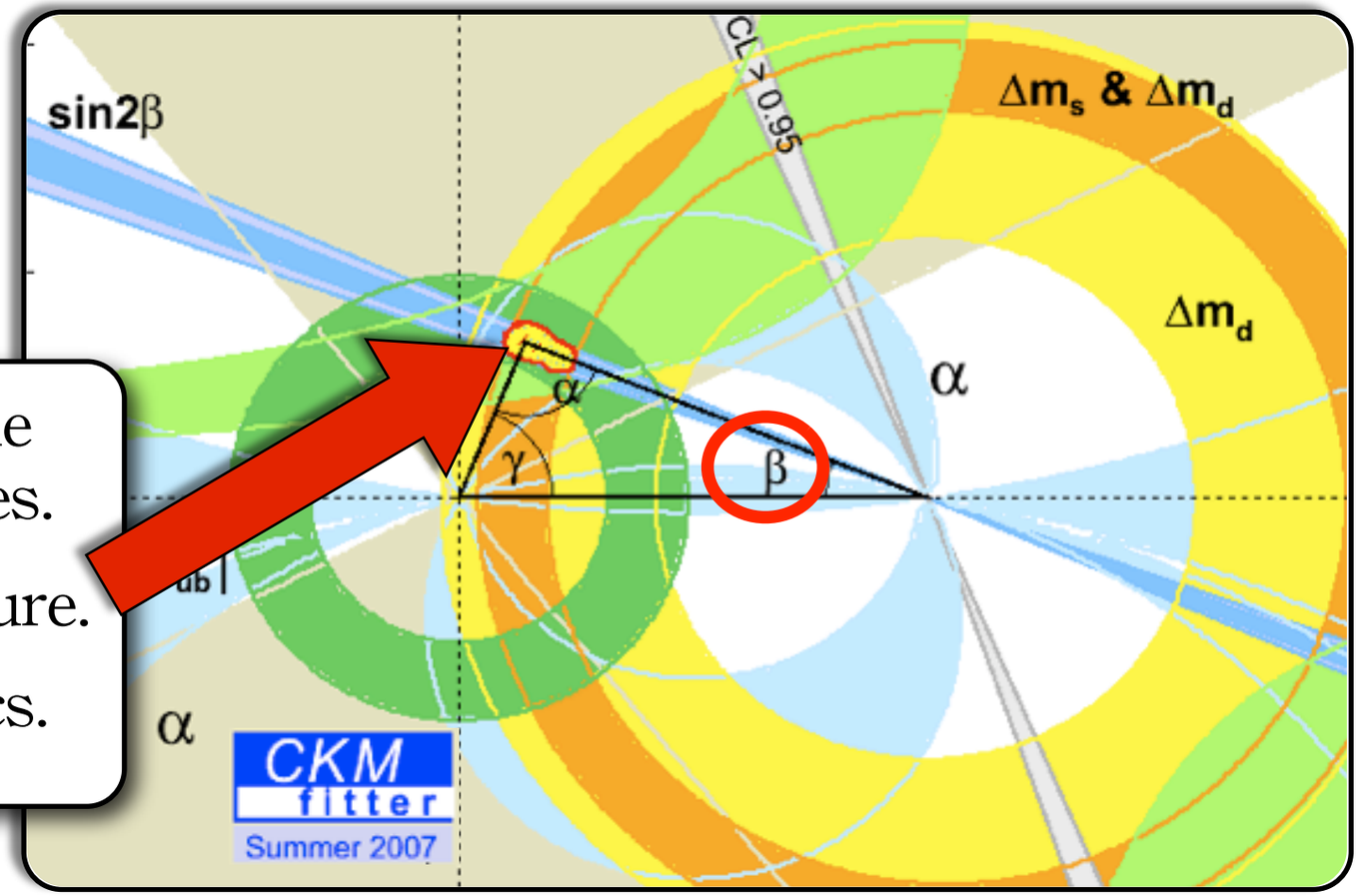


$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$(\beta, \alpha, \gamma) = (\phi_1, \phi_2, \phi_3)$$

Overconstraining the triangle

- Measure the sides and angles of the unitary triangle in diverse processes.
- Agreement confirms the CKM picture.
- Disagreement indicates new physics.



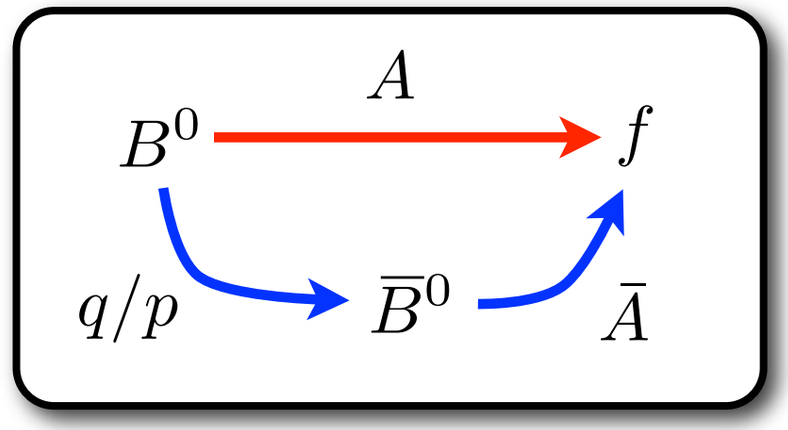
Wassili Kandinksy
Composition VIII, 1923

Mixing-induced CP violation

- For B meson pairs, produced coherently in $\Upsilon(4S) \to B^0\overline{B}^0$, time dependent decay rate asymmetry (to CP eigenstate f):

$$A_f(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = -S_f \sin(\Delta m_B t) + C_f \cos(\Delta m_B t)$$

- Final state f is reached from B^0 and $\overline{B}^0$, so amplitudes for decay and mixing+decay interfere:



- We define S_f and C_f in terms of λ_f:

$$S_f \equiv \frac{-2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

- Interference causes $\mathrm{Im}\ \lambda_f \neq 0$, though $|\lambda_f| = 1$.

$$\lambda_f \equiv \eta_f \frac{q}{p}\frac{\overline{A}_{\bar{f}}}{A_f}$$

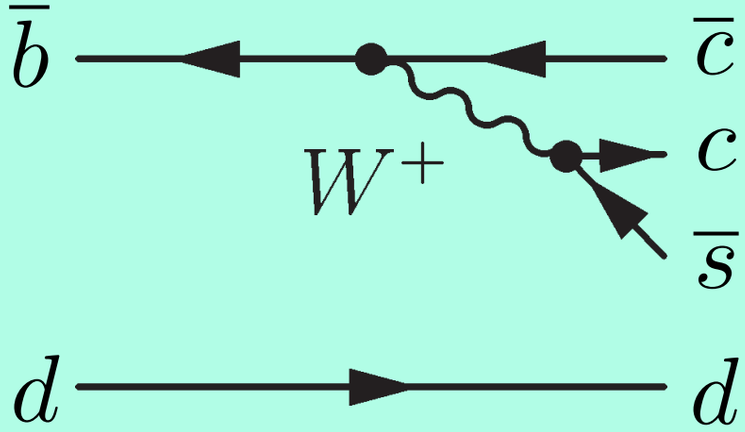
- $\frac{\overline{A}_{\bar{f}}}{A_f}$ ← ratio of decay amplitudes
- $\frac{q}{p}$ ← mixing amplitude
- η_f ← CP eigenvalue

$S_{c\bar{c}s} = \sin 2\beta$

- Tree dominated $b \to c\bar{c}s$ decays.
  - $B^0 \to J/\psi K^0_S$
  - $B^0 \to J/\psi K^0_L$,
  - $B^0 \to \psi(2S) K^0_S$,
  - $B^0 \to J/\psi K^{*,0}$ etc.

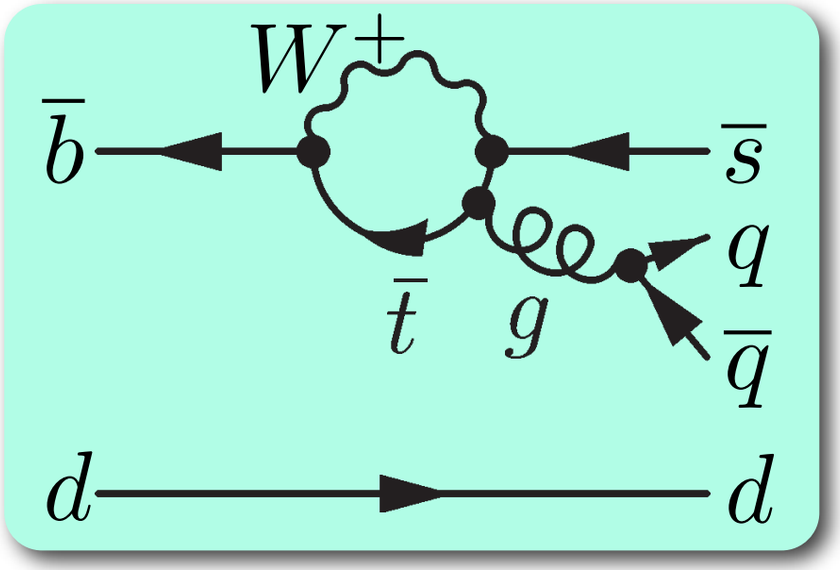
- Theoretically very clean, in SM:

$$\begin{aligned} S &= \sin 2\beta \\ C &= 0 \end{aligned}$$



"Golden mode" :
- large branching fraction (~10^{-3}).
- good reconstruction efficiency (30%).
- experimentally clean signature.

$S_f = \sin 2\beta_{\rm eff}$



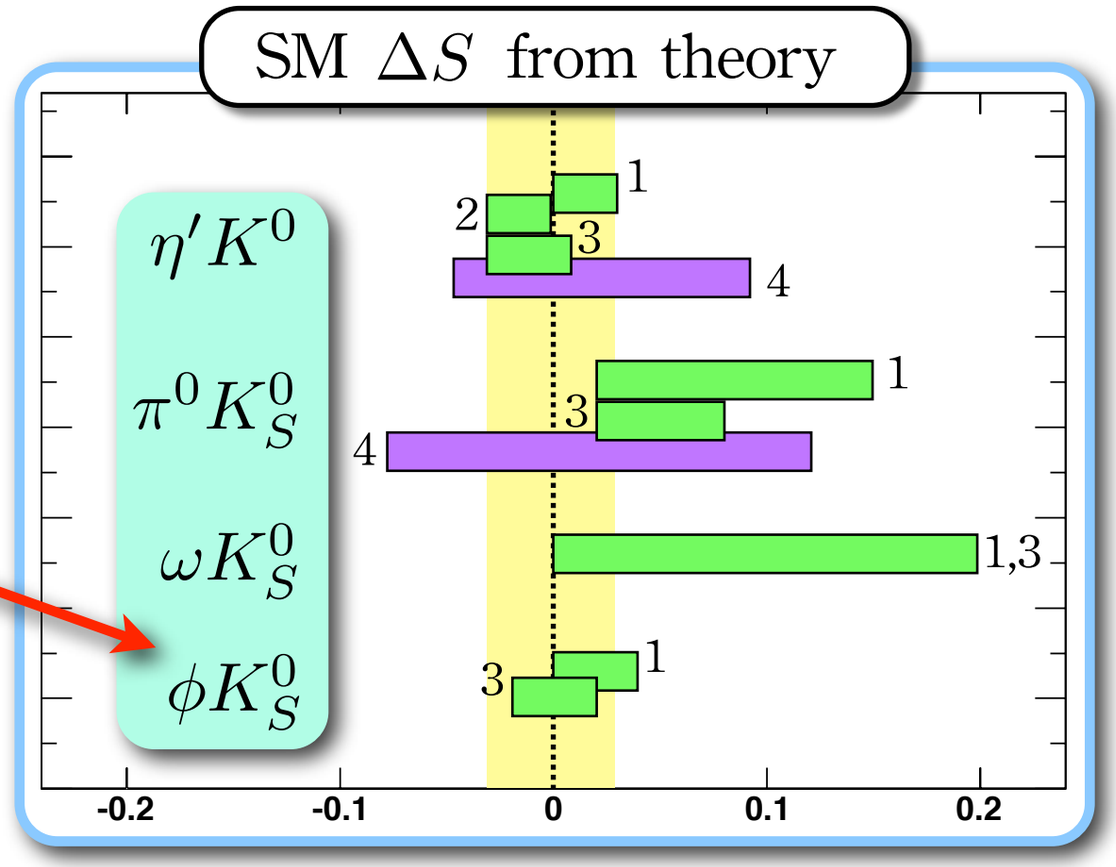
- Penguin dominated $b \to q\bar{q}s$ decays.
  - $B^0 \to \eta' K^0, \phi K^0$, etc.
- Pollution from secondary amplitudes:

$$\begin{aligned} S_f &\simeq \sin 2\beta \equiv \sin 2\beta_{\rm eff} \\ C_f &\simeq 0 \end{aligned}$$

- In clean modes, SM suggests

$$\Delta S \equiv \sin 2\beta_{\rm eff} - \sin 2\beta \simeq 0.03$$

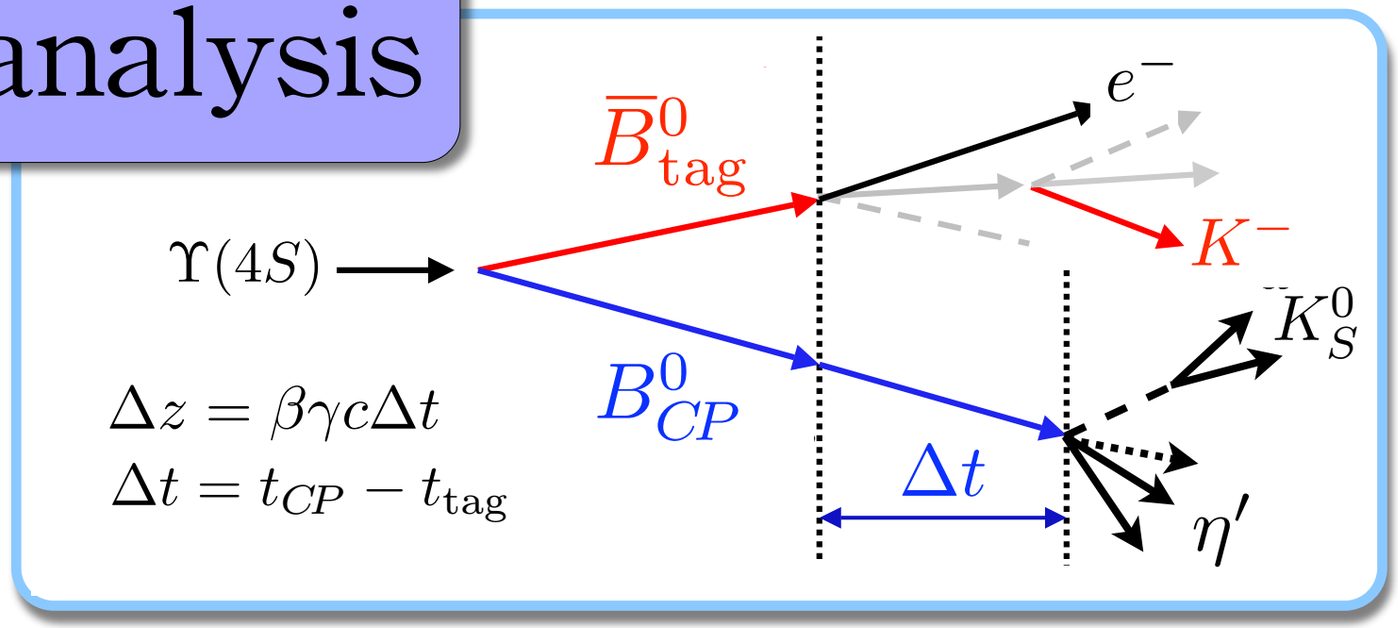
- Sensitive to new particles in loop.
- Large ΔS indicates new physics.



[1]QCDF Beneke, PLB620, 143 (2005)
[2]SCET/QCDF Williamson, Zupan, PRD74, 014003 (2006)
[3]QCDF Cheng, Chua, Soni, PRD72, 014006 (2005)
[4]SU(3) Gronau, Rosner, Zupan, PRD74, 093003 (2006)

Time dependent analysis

- Fully reconstruct B_{CP}; partially reconstruct $B_{\rm tag}$.
  - Measure Δz, convert to Δt.
  - Determine flavor of $B_{\rm tag}$.



Effective tagging efficiency:

$Q = (31.2 \pm 0.3)\%$ (Babar)

$Q = (29.0 \pm 0.1)\%$ (Belle)

$Q = \epsilon(1-2w)^2$

ϵ : efficiency

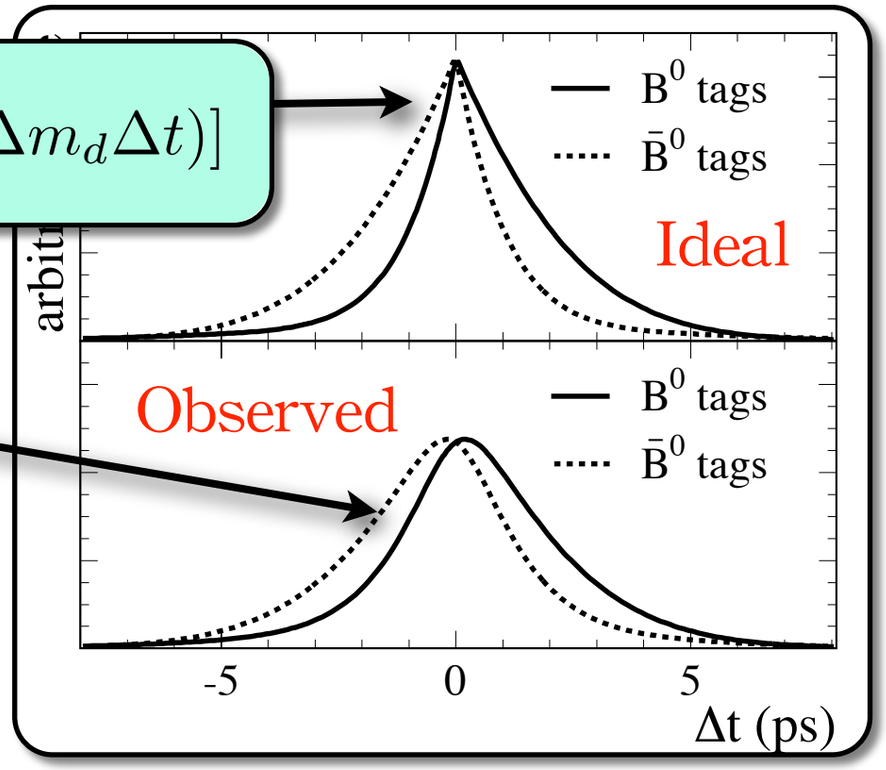
w : mistag rate

- Δt and flavor tag ($\pm$) go into decay rate:

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm (-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\right]$$

- Modify $f_\pm(\Delta t)$ for experimental Δt resolution and tagging performance.

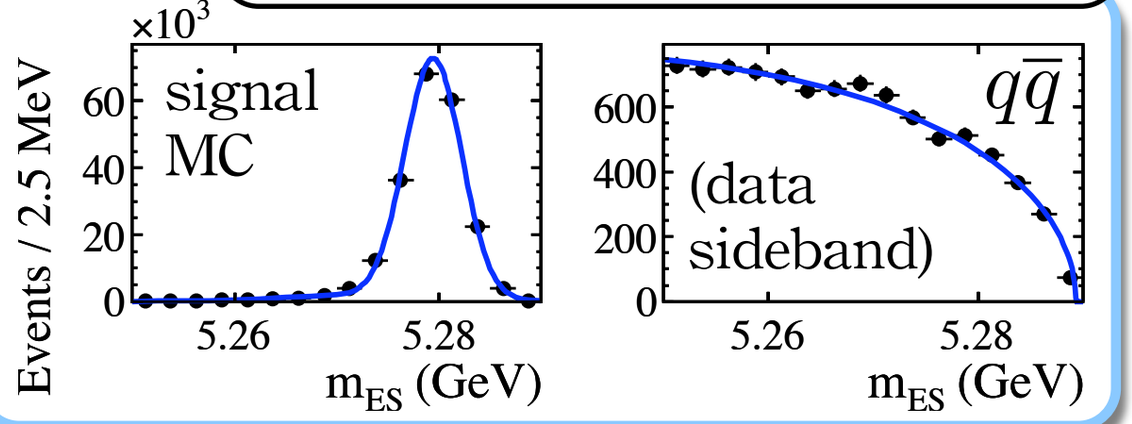
- Parameters of $f_\pm(\Delta t)$ obtained from a large sample of fully reconstructed self-tagging B decays.



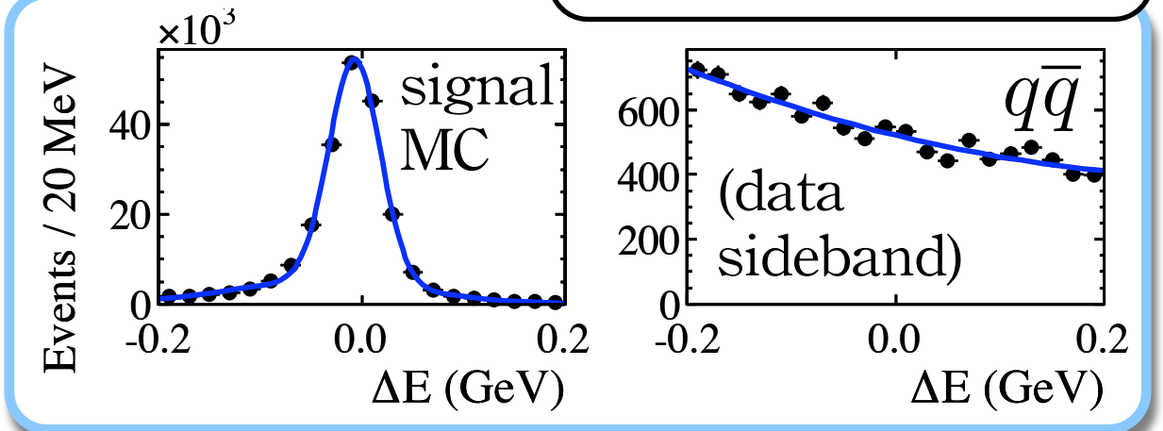
Maximum Likelihood Fit

- Components for signal, $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$, charmed and charmless $B\overline{B}$ decays.
- Discriminate with variables related to B meson kinematics:

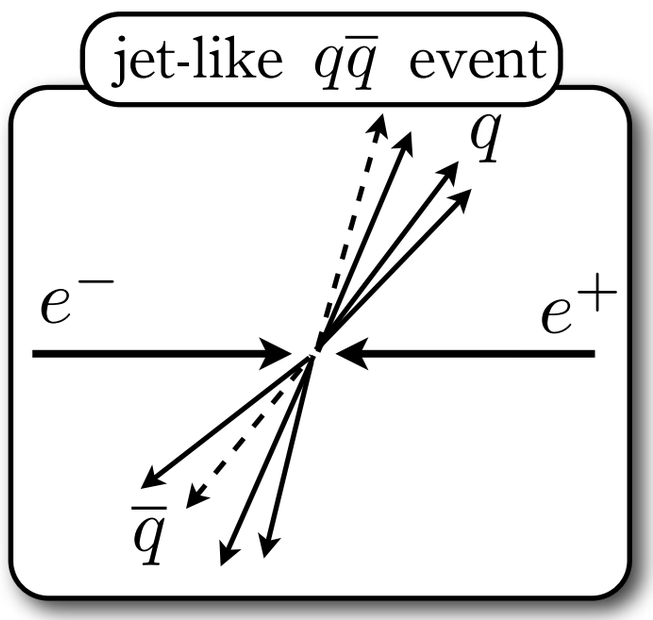
$m_{\rm ES} \equiv M_{bc} \equiv \sqrt{E^2_{\rm beam} - \mathbf{p}^{*2}_B}$

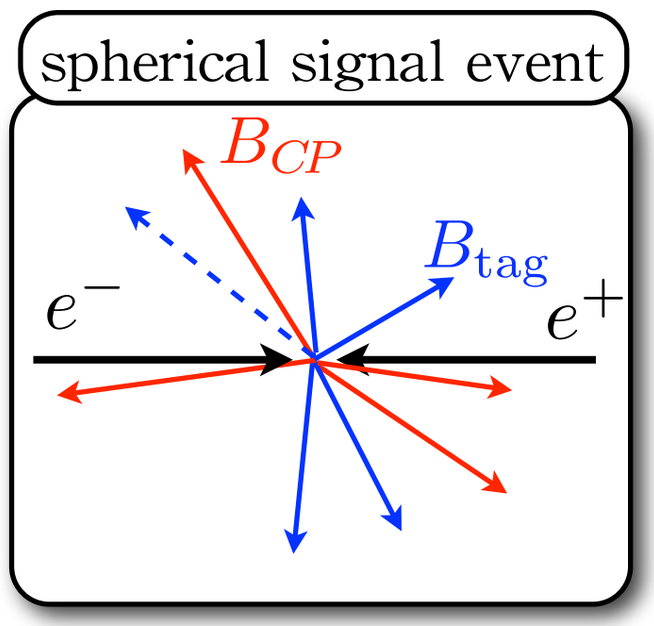


$\Delta E \equiv E^*_B - E_{\rm beam}$



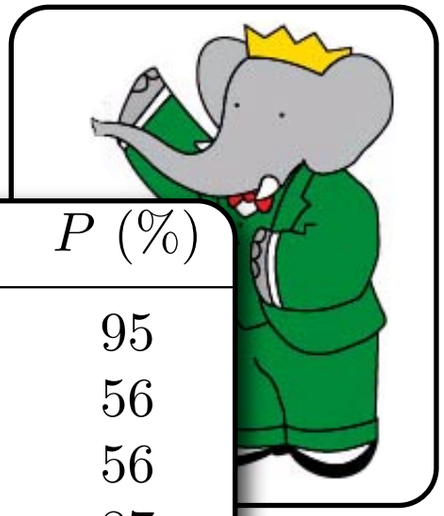
- Variables that exploit differing event topologies:
  - Babar`s Fisher discriminant ($\mathcal{F}$).
  - Belle`s likelihood ratio ($\mathcal{R}_{s/b}$).

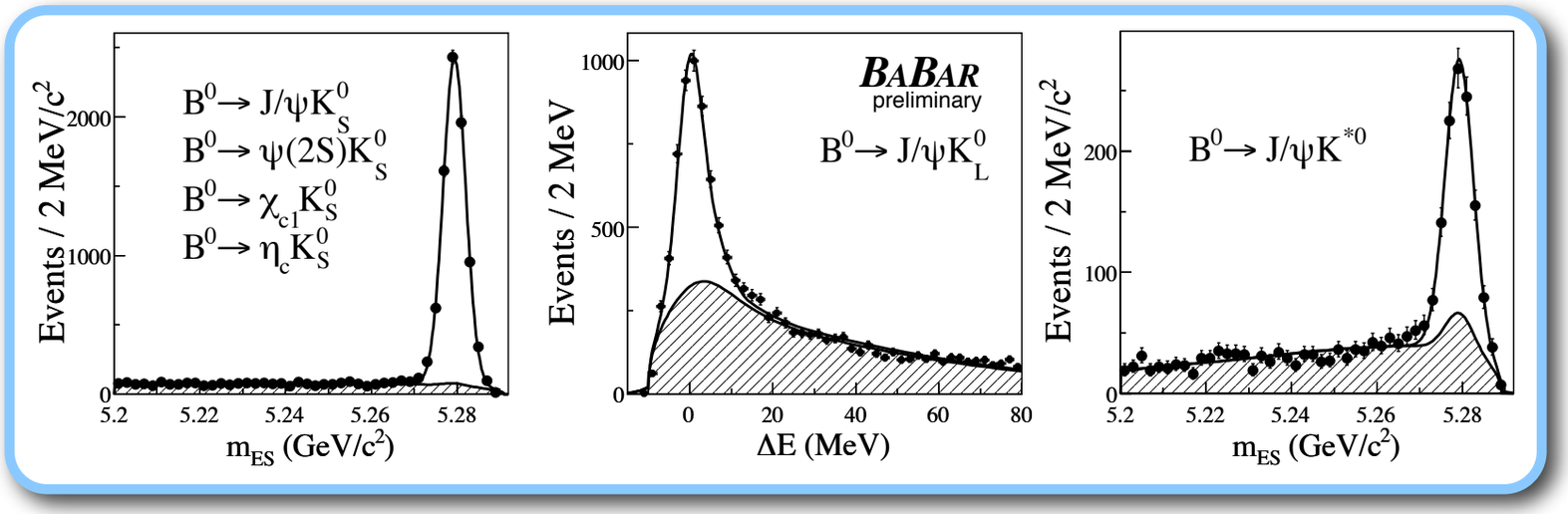




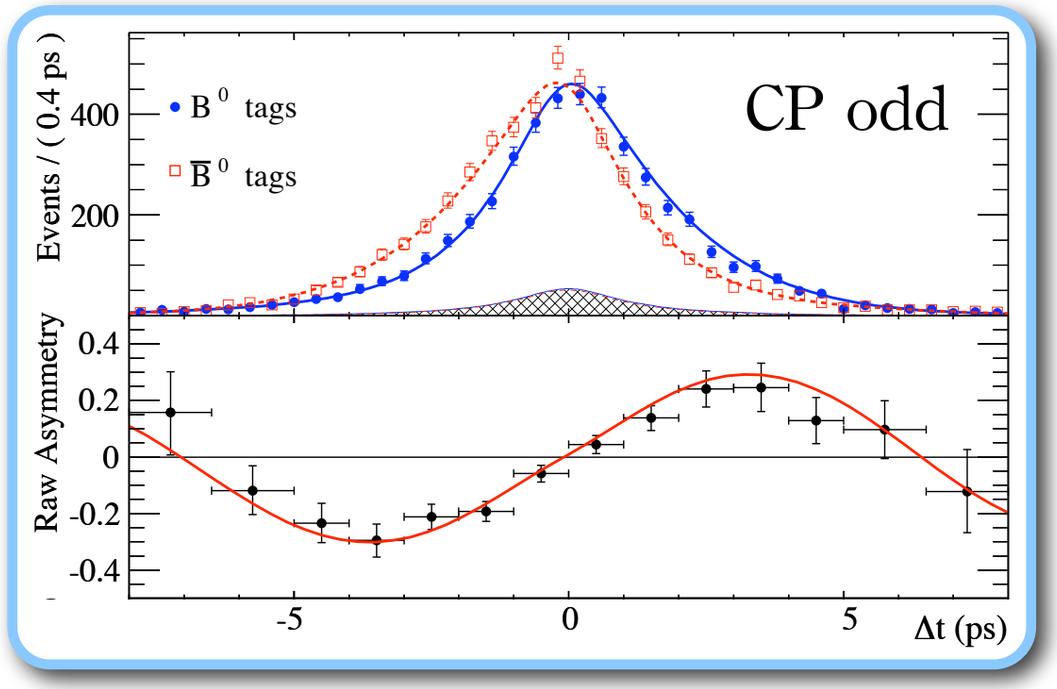
$b \to c\bar{c}s$ modes

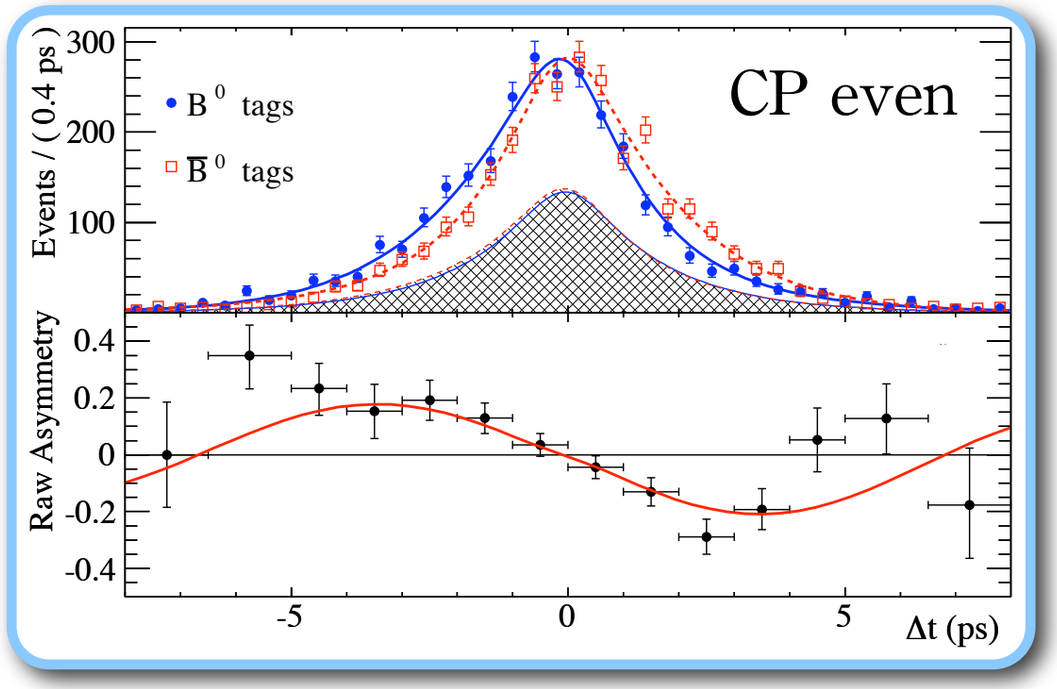
arXiv:0808.1903 (2008), 465M $B\bar{B}$ (accepted by PRD)





Mode	$N_{\rm evts}$	P (%)
$J/\psi K^0_S$	9073	95
$J/\psi K^0_L$	7813	56
$J/\psi K^*_0$	1735	56
$\psi(2S)K^0_S$	1157	87
$\chi_{c1}K^0_S$	517	88
$\eta_c K^0_S$	512	79
Total	20807	76



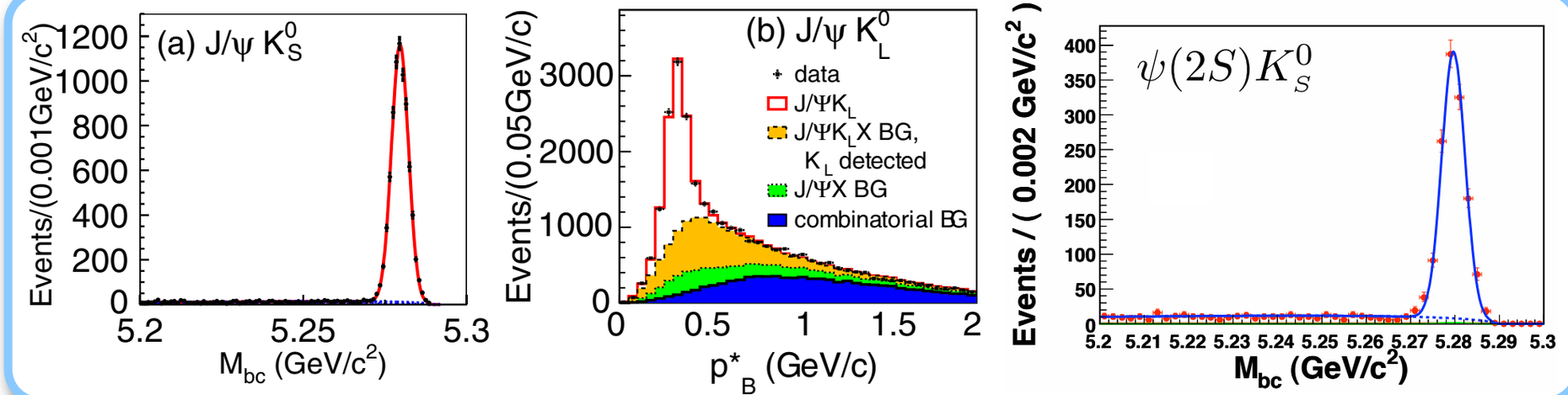


$$S = 0.691 \pm 0.029 \pm 0.014$$
$$C = 0.027 \pm 0.020 \pm 0.016$$

Dominant systematic:
- S: Δt resolution model.
- C: Interference in tag-side DCSD.

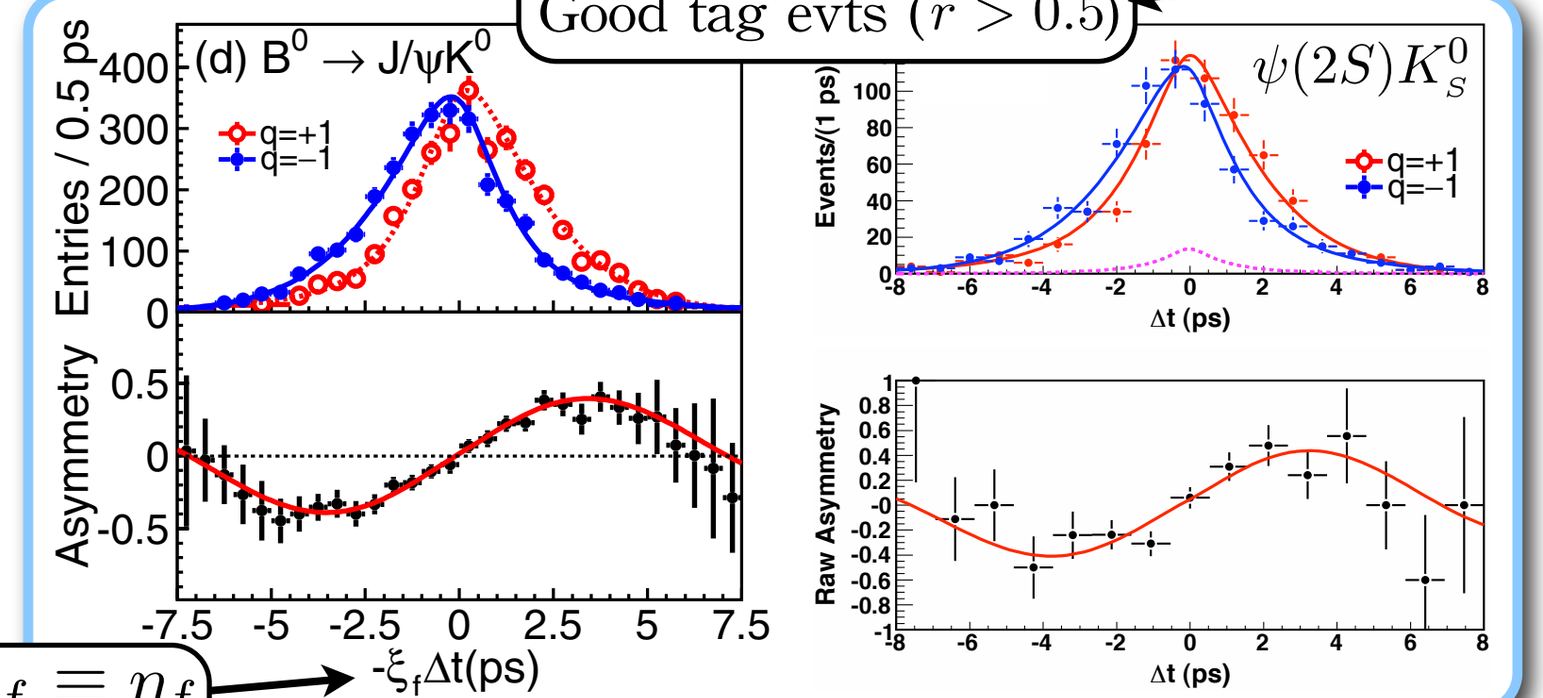
$b \to c\bar{c}s$ modes

PRL 98 031802 (2007), 535M $B\bar{B}$



Good tag evts ($r > 0.5$)

r is output of tagging algo.



$\xi_f \equiv \eta_f$

Mode	$N_{\rm evts}$	P (%)
$J/\psi K^0_S$	7484	–
$J/\psi K^0_L$	6512	–
$\psi(2S)K^0_S$	1284	92

$S = 0.642 \pm 0.031 \pm 0.017$
$C = 0.018 \pm 0.021 \pm 0.014$

$S = 0.720 \pm 0.090 \pm 0.030$
$C = 0.040 \pm 0.070 \pm 0.050$

Dominant systematics:

- S: vertex reconstruction.
- C: interference in tag-side DCSD.

$B^0 \to \eta' K^0$

- Large BF (65×10^{-6}) yields small errors on S_f and C_f.
- 7 decay channels:
  $\eta'(\ \rho\gamma,\ \eta_{\gamma\gamma}\pi^+\pi^-,\ \eta_{3\pi}\pi^+\pi^-)\ K_S(\pi^+\pi^-)$
  $\eta'(\ \rho\gamma,\ \eta_{\gamma\gamma}\pi^+\pi^-)\ K_S(\pi^0\pi^0)$
  $\eta'(\ \eta_{\gamma\gamma}\pi^+\pi^-,\ \eta_{3\pi}\pi^+\pi^-)\ K_L$

Mode	Event yields Belle	*BABAR*
$\eta' K_S^0$	1421 ± 46	1959 ± 58
$\eta' K_L^0$	454 ± 39	556 ± 38

535M $B\overline{B}$

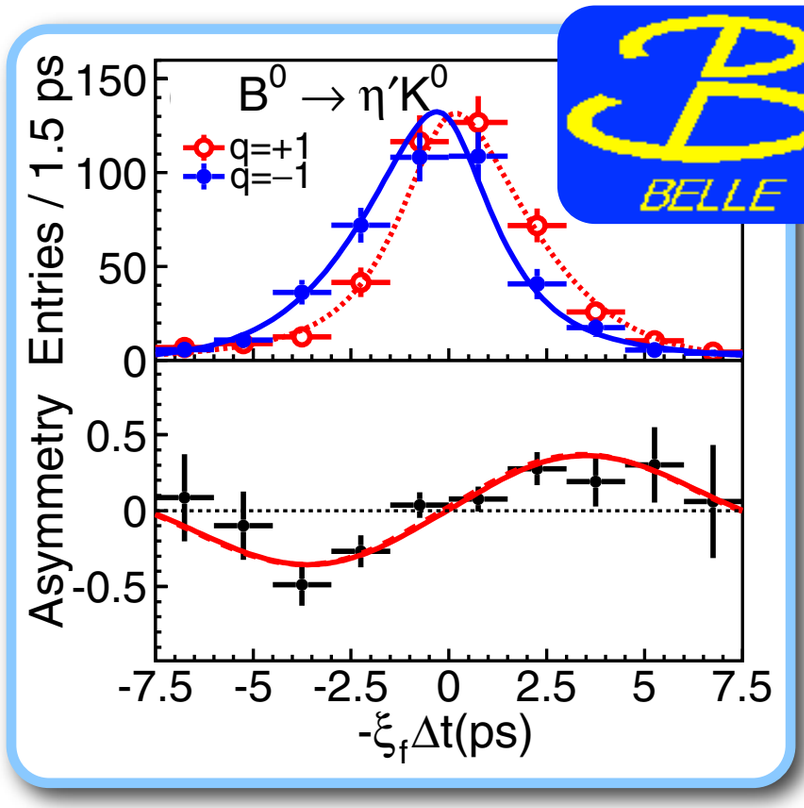
Signal enhanced with cut on ΔE and $\mathcal{R}_{s/b}$

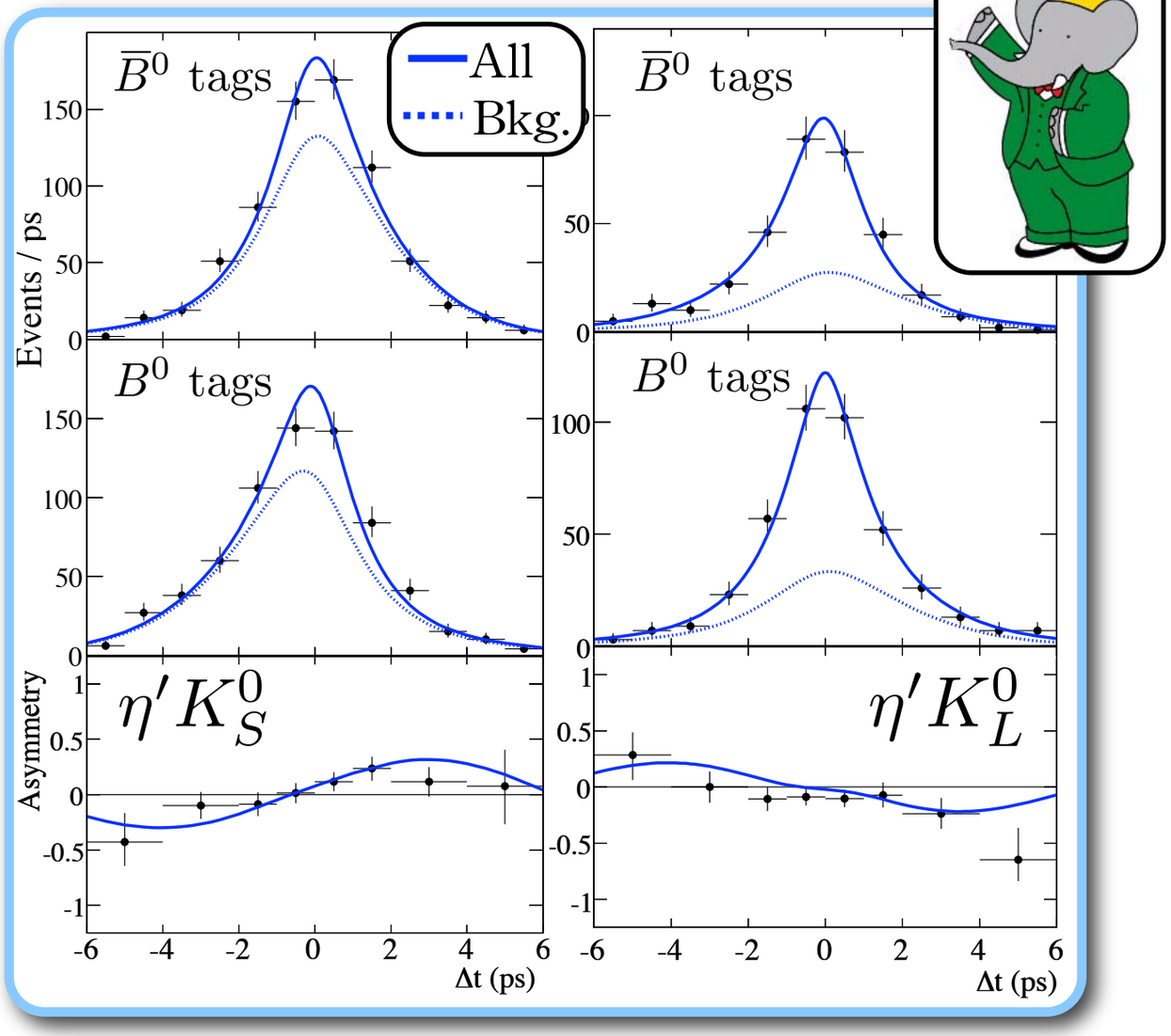
465M $B\overline{B}$

Signal enhanced with cut on likelihood ratio

$B^0 \to \eta' K^0$

BABAR : PRD 79 052003 (2009)
Belle : PRL 98 031802 (2007)





Dominant systematic for both:
- S: Δt resolution model.
- C: Interference in tag-side DCSD.

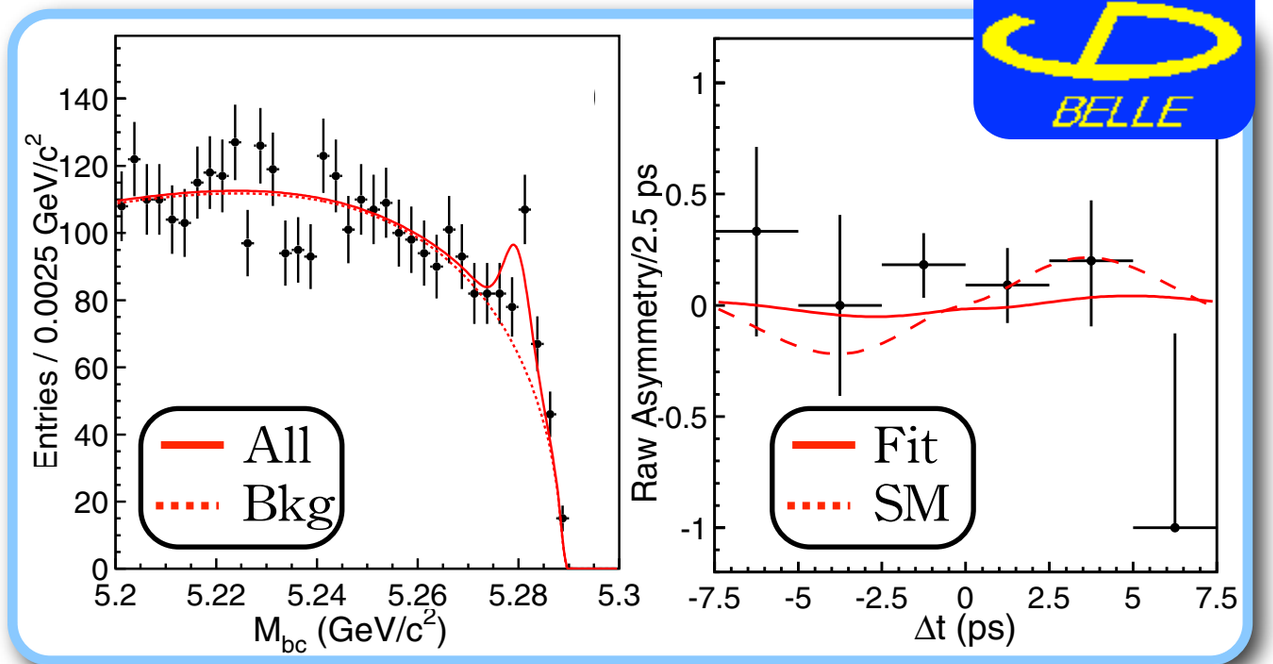
Mode	Belle	*BABAR*
$-\eta S_{\eta' K^0_S}$	0.67 ± 0.11	$0.53 \pm 0.08 \pm 0.02$
$C_{\eta' K^0_S}$	0.03 ± 0.07	$-0.11 \pm 0.06 \pm 0.02$
$-\eta S_{\eta' K^0_L}$	0.46 ± 0.24	$0.82 \pm 0.19 \pm 0.02$
$C_{\eta' K^0_L}$	-0.09 ± 0.16	$0.09 \pm 0.14 \pm 0.02$
$S_{\eta' K^0}$	$0.64 \pm 0.10 \pm 0.04$	$0.57 \pm 0.08 \pm 0.02$
$C_{\eta' K^0}$	$0.01 \pm 0.07 \pm 0.05$	$-0.08 \pm 0.06 \pm 0.02$

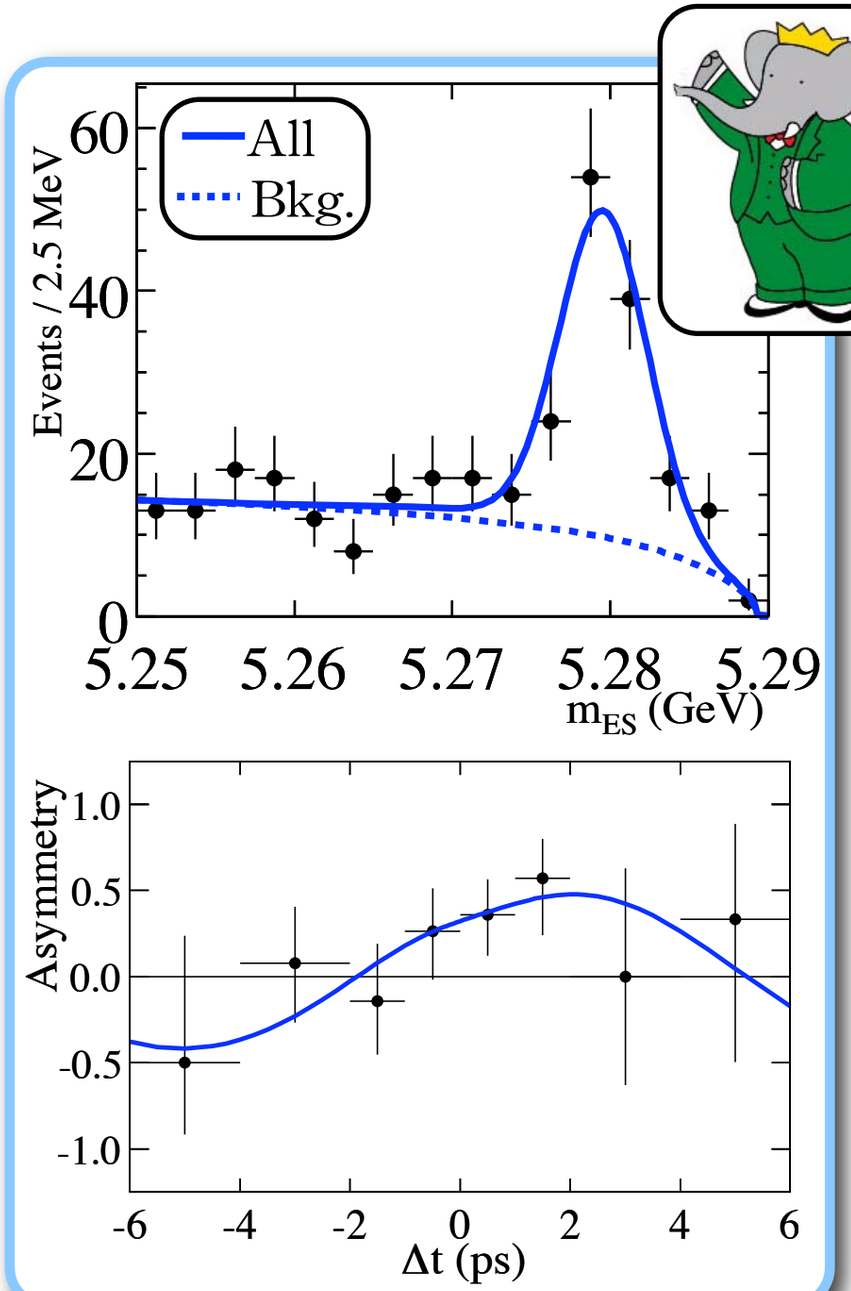
$B^0 \to \omega K^0_S$

BABAR : PRD 79 052003 (2009), 465M $B\overline{B}$
Belle : PRD 76 091103 (2007), 535M $B\overline{B}$

- Branching fraction ~ 6 x 10^{-6}.
- Belle uses ω mass.
- Babar uses ω mass and helicity.
- Reconstruct:

$$\omega \to \pi^+\pi^-\pi^0, K^0_S \to \pi^+\pi^-$$



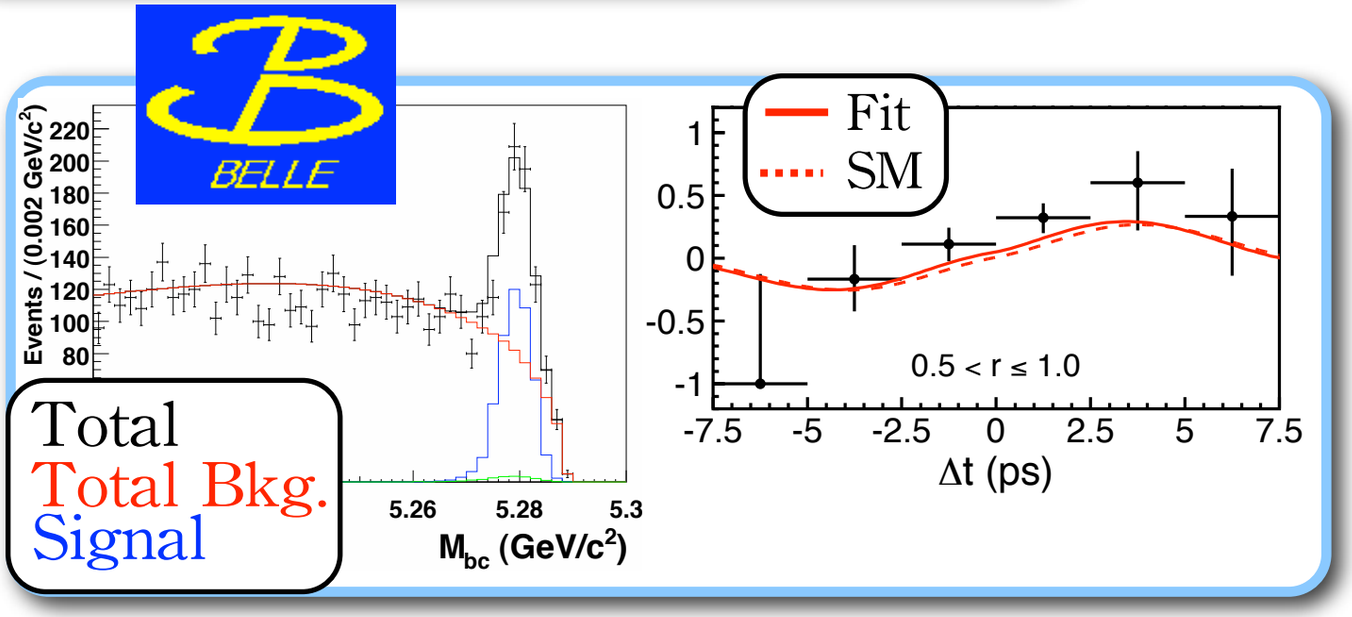


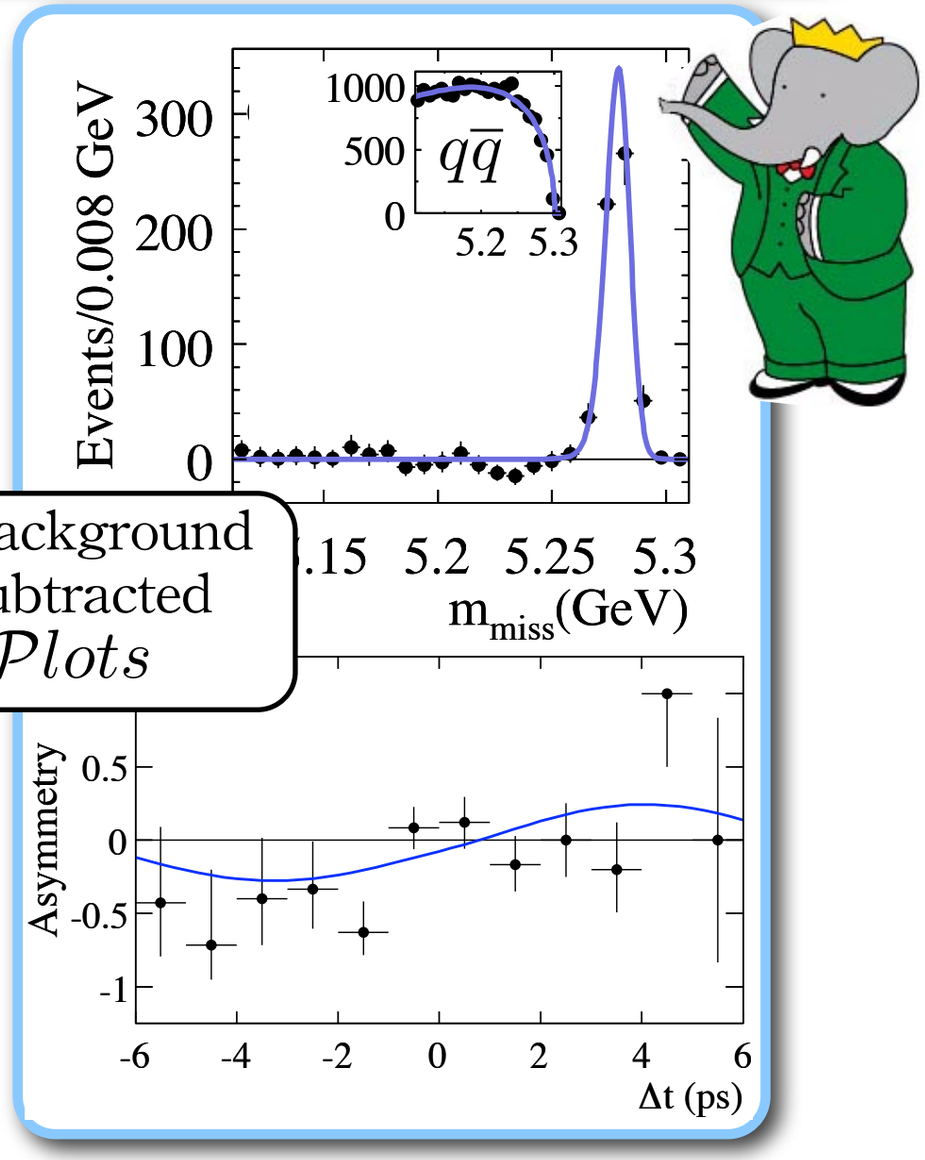
	Belle	*BABAR*
$N_{\rm evts}$	118 ± 18	163 ± 18
$S_{\omega K^0_S}$	$0.11 \pm 0.46 \pm 0.07$	$0.55^{+0.26}_{-0.29} \pm 0.02$
$C_{\omega K^0_S}$	$0.09 \pm 0.29 \pm 0.06$	$-0.52^{+0.22}_{-0.20} \pm 0.03$

$B^0 \to \pi^0 K^0_S$

BABAR : PRD 79 052003 (2009), 465 M $B\overline{B}$
Belle : 0809.4366 (2008), 657 M $B\overline{B}$

- No tracks from B decay vertex!
- 60% of signal B candidates make hits in inner silicon tracker.
- Obtain Δt in these events with constraints on average interaction point (and B lifetime for Babar).





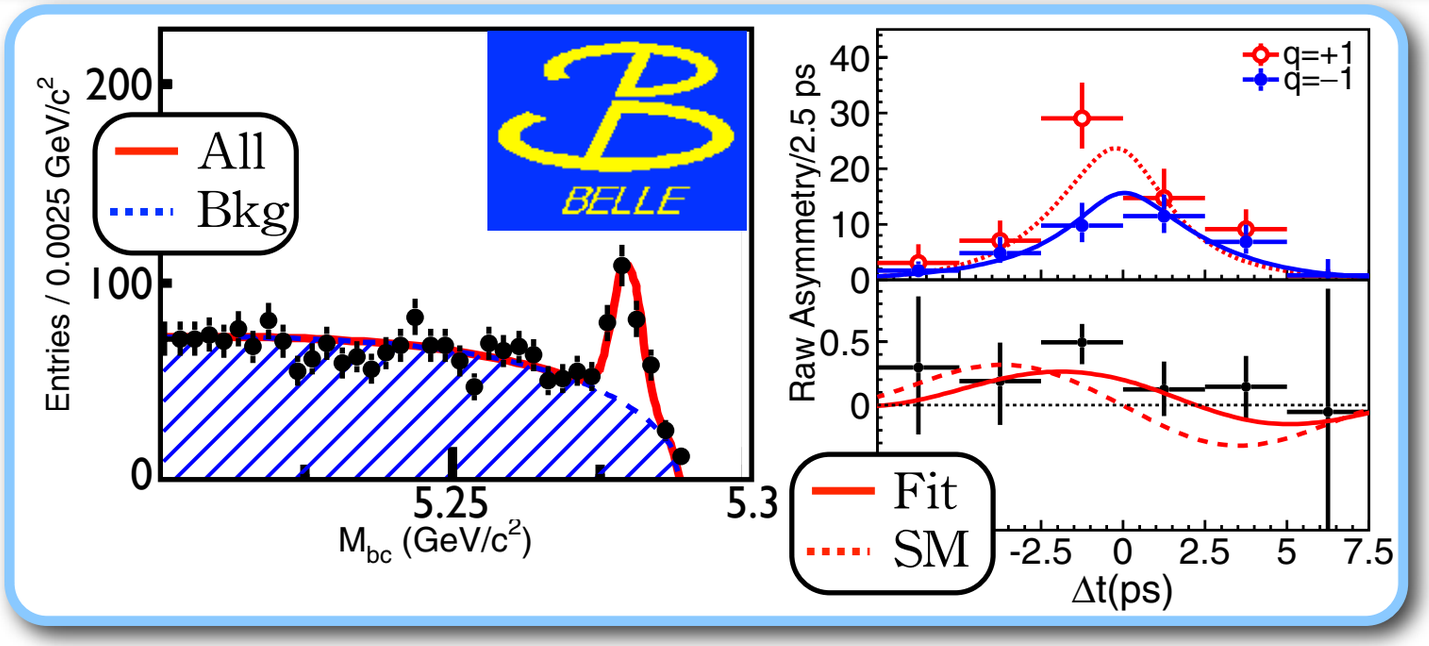
	Belle	*BABAR*
$N_{\pi^0 K^0_S}$	657 ± 37	556 ± 32
$N_{\pi^0 K^0_L}$	285 ± 52	–
S	$0.67 \pm 0.31 \pm 0.08$	$0.55 \pm 0.20 \pm 0.03$
C	$0.14 \pm 0.13 \pm 0.06$	$0.13 \pm 0.13 \pm 0.03$

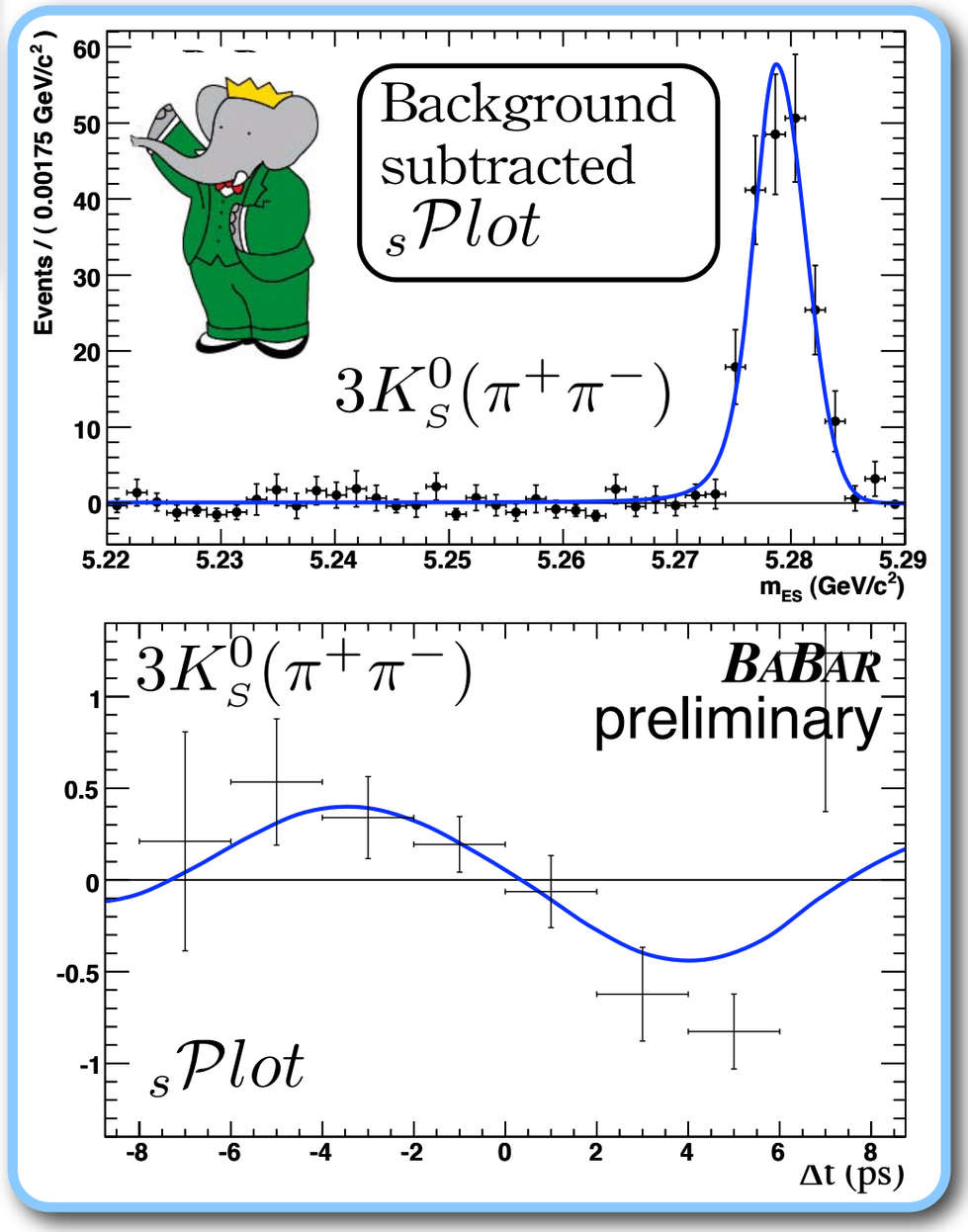
- All events constrain C.
- Belle also uses $\pi^0 K^0_L$ events to constrain C.

$B^0 \to K^0_S K^0_S K^0_S$

BABAR : CKM 2008 preliminary, 465M $B\overline{B}$
Belle : PRL 98 031802 (2007), 535M $B\overline{B}$

- Reconstruct:
  $2K^0_S(\pi^+\pi^-)K^0_S(\pi^0\pi^0)$ and $3K^0_S(\pi^+\pi^-)$
- Again, no tracks from B decay vertex.
- Require one K^0_S to make hits in inner tracker.
- Constrain average interaction point and B lifetime.

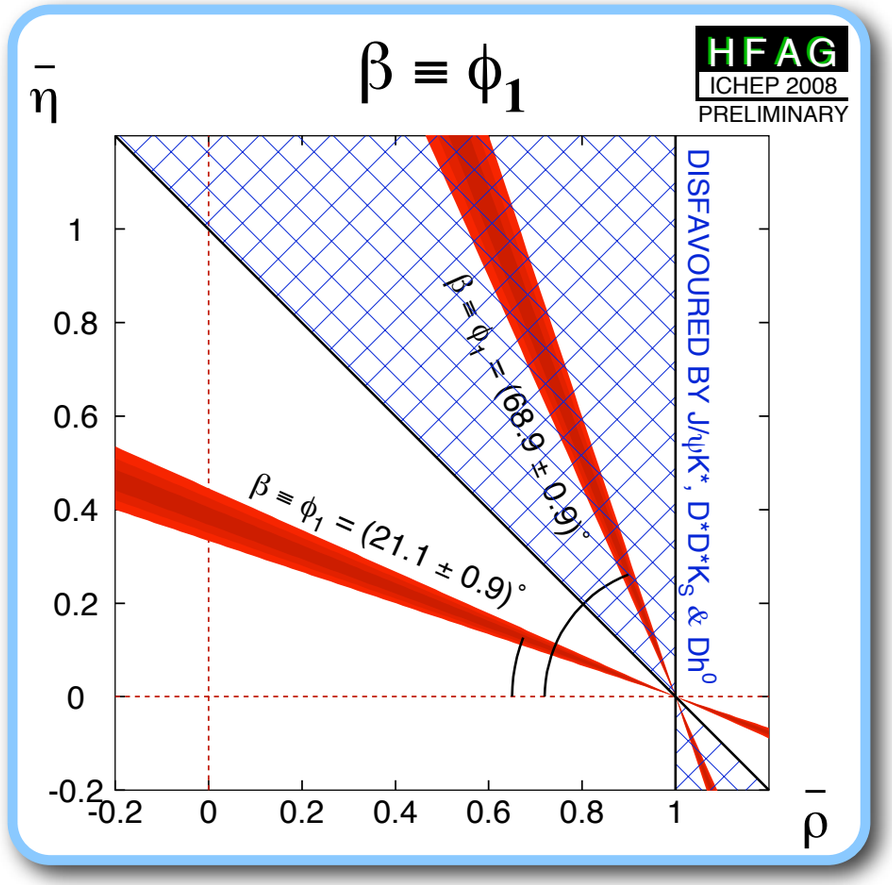


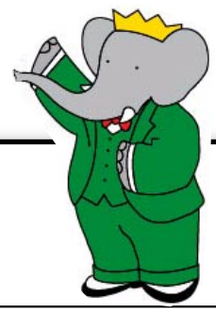


	Belle	*BABAR*
$N_{\rm tag}$	185 ± 17	274 ± 21
$-\eta S$	$0.30 \pm 0.32 \pm 0.08$	$0.90\ ^{+0.20}_{-0.18}\ ^{+0.04}_{-0.03}$
C	$-0.31 \pm 0.20 \pm 0.07$	$-0.16 \pm 0.17 \pm 0.03$

$\frac{\pi}{2} - \beta$ Ambiguity

- Interference between CP-even and -odd amplitudes makes $J/\psi K^{*0}, D^{(*)}D^{(*)}K_S^0$ sensitive to $\cos 2\beta$.
- Interference in $D^{(*)}$ Dalitz plot makes $D^{(*)}h^0$ sensitive to $\cos 2\beta$.
- Interference in DP makes $K^+K^-K_S^0$ sensitive to β.





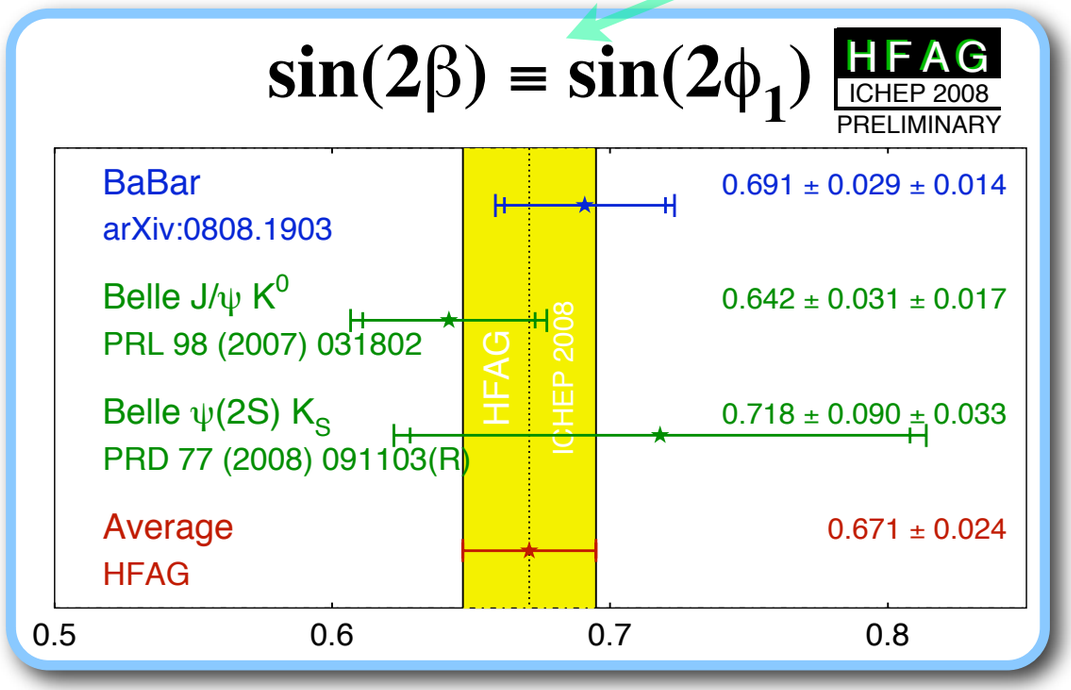
Final State	$\cos 2\beta$	C.L. for $\cos 2\beta > 0$	BELLE $\cos 2\beta$	C.L. for $\cos 2\beta > 0$
$D^{(*)+}D^{(*)-}K_S^0$	$0.38 \pm 0.24 \pm 0.05$ [1]	94%	$-0.23\ ^{+0.43}_{-0.41} \pm 0.13$ [2]	–
$D^{(*)0}h^0$	$0.42 \pm 0.49 \pm 0.16$ [3]	86%	$1.87\ ^{+0.40\ +0.22}_{-0.53\ -0.32}$ [4]	98.3%
$J/\psi K^{*0}$	$3.32^{+0.76}_{-0.96} \pm 0.27$ [5]	89%	$0.56 \pm 0.79 \pm 0.11$ [6]	–
$K^+K^-K_S^0$	$\beta = (29.5 \pm 4.5 \pm 1.5)^\circ$ [7]	4.8σ	$\beta_{\phi K_S^0} = (21.2^{+\ 9.8}_{-10.4} \pm 2.0)^\circ$ [8]	–

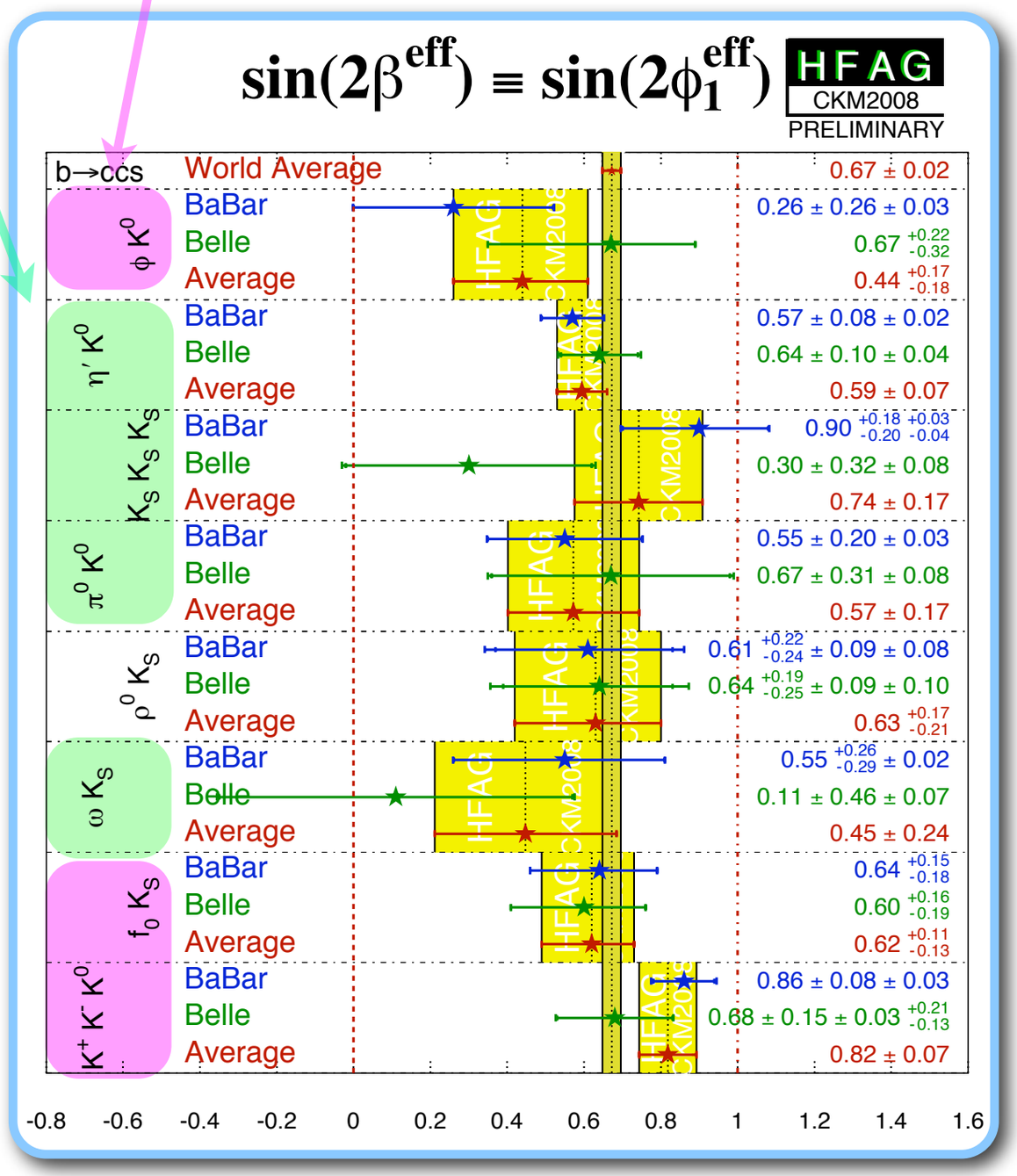
[1] PRD 74 091101 (2006) (230M BB)
[2] PRD 76 072004 (2007) (449M BB)
[3] PRL 99 231802 (2007) (383M BB)
[4] PRL 97 081801 (2006) (386M BB)
[5] PRD 71 032005 (2005) (88M BB)
[6] PRL 95 091601 (2005) (275M BB)
[7] arXiv:0808.0700 (2008) (465M BB)
[8] ICHEP08 preliminary (657M BB)

Summary

This talk

"CPV at B factories, $B \to K\pi$, $b \to s\gamma$"
Yu Nakahama (Heavy Flav. & CKM-3)





- New physics is not dominant.
- At LHC: Difficult to trigger on ϕK^0; impossible to trigger on $\eta' K^0$.
- At Super Flavor Factories:
  - Measurements of $\beta_{\rm eff}$ and β systematics limited.
  - Experimental/theoretical uncertainties comparable.

Babar systematics on $\sin 2\beta$ from $J/\psi K^0$

Source/sample		Full	$J/\psi\, K^0$	$J/\psi\, K^0_S$	$J/\psi\, K^0_L$
Beamspot	S_f	0.0013	0.0021	0.0027	0.0000
	C_f	0.0006	0.0010	0.0021	0.0001
Mistag differences	S_f	0.0077	0.0057	0.0059	0.0083
	C_f	0.0047	0.0069	0.0053	0.0052
Δt resolution	S_f	0.0067	0.0068	0.0069	0.0071
	C_f	0.0027	0.0029	0.0034	0.0070
$J/\psi\, K^0_L$ background	S_f	0.0057	0.0063	0.0000	0.0271
	C_f	0.0007	0.0008	0.0000	0.0036
Background fraction	S_f	0.0046	0.0034	0.0036	0.0044
and CP content	C_f	0.0029	0.0021	0.0009	0.0107
m_{ES} parameterization	S_f	0.0022	0.0020	0.0026	0.0006
	C_f	0.0004	0.0005	0.0008	0.0002
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.0030	0.0033	0.0036	0.0040
	C_f	0.0013	0.0012	0.0011	0.0013
Tag-side interference	S_f	0.0014	0.0014	0.0014	0.0014
	C_f	0.0143	0.0143	0.0143	0.0143
Fit bias	S_f	0.0023	0.0044	0.0041	0.0063
(MC statistics)	C_f	0.0026	0.0044	0.0041	0.0060
Total	S_f	0.0135	0.0131	0.0119	0.0311
	C_f	0.0164	0.0187	0.0167	0.0270